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THEORETICAL EVALUATION OF THE DUCTED-FAN TURBOJET ENGINE

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Cleveland, Ohio

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SUMMARY

The calculated performance of three series of ducted-fan turbojet engines designed for obtaining maximum net thrust per pound of air handled, minimum net-thrust specific fuel consumption, and maximum flight range is presented. The performance of these engines with thrust augmentation by auxiliary burning for obtaining maximum thrust and without auxiliary burning for achieving maximum economy or maximum range is analyzed at flight Mach numbers of 0.3 to 0.9 at an altitude of 30,000 feet.

A comparison is made between the characteristics of the ducted-fan turbojet and turbojet engines, with or without tail-pipe burning, operating at conditions of maximum thrust per pound of air handled, minimum net-thrust specific fuel consumption, and maximum range. Turbine-propeller-engine data are also included for additional comparison. The range characteristics of all engines are presented for pay-load-to-gross-weight ratios of 0.0 to 0.4.

The comparisons indicate that:

1. The turbojet engine with tail-pipe burning produced greater net thrust per pound of air handled than any configuration of the ducted-fan turbojet engine.

2. The turbine-propeller engine provided the lowest specific fuel consumption and the maximum range of any of the engines considered below a flight Mach number of 0.6 for pay-load-to-gross-weight ratios of 0.3 or less.

3. Maximum range for both the ducted-fan engine and the turbojet engine occurred at a flight Mach number of approximately 0.6. At this speed and for zero pay load, the ducted-fan engine showed a 5-percent increase in range over the turbojet engine. At higher flight Mach numbers or at a pay-load-to-gross-weight ratio of 0.3 or greater, the increase in range was negligible.

If flight speeds do not exceed a Mach number of approximately 0.6, the turbine-propeller engine offers the most favorable performance of any of the engines considered. At higher flight Mach numbers, the turbojet engine with tail-pipe burner (operating for thrust augmentation and nonoperative for range) should realize the greatest performance flexibility of any of the engines considered.

INTRODUCTION

The ducted-fan type of turbojet engine represents an attempt to combine the fuel economy of a propeller-type engine with the light weight of the turbojet engine. A ducted-fan turbojet engine may be considered as a modification of the turbojet engine, which requires the installation of a more powerful turbine to drive a relatively small-diameter multibladed propeller in addition to the normal compressor. All or part of the air (depending on the configuration) that is handled by the propeller, or fan, is passed through a separate duct. Burners are installed in the separate duct to augment the thrust when necessary. These engines are hereinafter designated ducted-fan engines. A schematic diagram of this type of engine is presented in figure 1; a turbojet-type engine is also shown for comparison.

For economy operation, the ducted-fan engine is intended to handle a greater mass of air at lower jet velocities (unheated outer-duct air) and hence attain a higher propulsive efficiency than a turbojet engine of equal thrust. The higher propulsive efficiency appears in the form of a lower specific fuel consumption. If the thrust per unit frontal area of the ducted-fan engine were made equal to that of the turbojet engine, it would be necessary to increase the air-handling capacity per unit frontal area of the ducted-fan engine beyond that of the turbojet engine.

The present investigation, which was conducted at the NACA Cleveland laboratory, is based, however, on the fact that if an increased air flow per unit area were possible for a ducted-fan engine it would also be possible for the turbojet engine. The ducted-fan engine should therefore have a lower specific fuel consumption and a lower thrust per unit frontal area than a comparable turbojet engine.

A survey of available literature reveals only incomplete information on the performance of ducted-fan engines. An American investigation (reference 1) indicates that at 400 to 500 miles per hour at altitudes of 30,000 to 35,000 feet the fuel economy of a ducted-fan engine is substantially better than that of a turbojet engine.

The investigation did not include engine operation with auxiliary burning. Considerable interest has been shown by the British in ducted-fan-engine performance and design. Results of static tests of such an engine operating without tail-pipe burning are presented in reference 2. Details of the Miles supersonic aircraft, which utilizes a ducted-fan engine with auxiliary burning, are presented in reference 3 but no engine performance data are given. Reference 4 mentions an experimental Power Jets ducted-fan engine but does not present performance data.

A theoretical analysis was therefore undertaken at the Cleveland laboratory to obtain information based on attainable values of specific fuel consumption and thrust per unit frontal area and to evaluate this information in terms of the speed-range-pay-load characteristics of the ducted-fan engine. The performance of three series of ducted-fan engines designed for obtaining maximum net thrust per pound of air handled, maximum economy, and maximum range is considered. The performance of the engines with thrust augmentation by auxiliary burning (simultaneous operation of all auxiliary burners) for obtaining maximum thrust and without auxiliary burning for achieving maximum economy or maximum range is analyzed at flight Mach numbers of 0.3 to 0.9 at an altitude of 30,000 feet.

The calculated characteristics of three series of turbojet engines (with or without thrust augmentation by tail-pipe burning) operating at conditions of maximum net thrust per pound of air handled, maximum economy, and maximum range are included to provide a means of evaluating the performance of the ducted-fan engines. Turbine-propeller engine data from reference 5 are also included for additional evaluation purposes. The range characteristics of all engines is presented for pay-load-to-gross-weight ratios of 0.0 to 0.4.

The terms "ducted-fan engines" and "turbojet engines" shall indicate herein engines equipped with cold auxiliary burners. In the case of the ducted-fan engine, the combination of outer-duct and tail-pipe burners is designated auxiliary burners (fig. 1(a)); in the case of the turbojet engine, the auxiliary burners are tail-pipe burners. The increased pressure drop and engine weight resulting from the presence of the cold burners penalize the performance of the maximum-economy and maximum-range engines. It is assumed, however, that future standard turbojet-type engines will include auxiliary burners as regular equipment to permit a choice between cruising economy and thrust augmentation.

BASIS OF ANALYSIS

Engine Performance

This analysis assumes that the working substance of all engine cycles is air. Variable specific heats are also assumed.

The properties of the gas were evaluated at the stations indicated in figure 1. (Corresponding stations of the two engines have the same identification.)

It is assumed that the compressor, or fan, will limit the air flow and that the diameter of the engine will be substantially that of the compressor, or fan. The air-flow limitation is considered to occur in the inlet stage of the compressor, or fan, by virtue of the attainment of a limiting Mach number. The size limitation assumes that the burners and the turbines are capable of handling the maximum air-flow capacity of the compressor without exceeding the diameter of the compressor. The maximum diameter of current axial turbojet engines occurs at the burners. However, increased compressor pressure ratios plus improved burner configurations for starting and extreme altitude conditions should permit the burners of future turbojet engines to stay within the compressor-diameter limitation. Analysis indicates that the diameter of the turbine does not have to be greater than that of the compressor. The condition of equal turbine and compressor diameter is nevertheless more difficult to satisfy in the case of turbine-propeller and ducted-fan types of engine wherein the turbine is required to develop excess shaft horsepower as compared with a turbojet-type engine.

It is also assumed that the compressors, or fans, of the turbojet and ducted-fan engines will be of the axial-flow type and will operate at the same values of air flow per unit frontal area. These assumptions permit the analysis to make use of the parameter net thrust per pound of air handled, which is then equivalent to net thrust per unit frontal area. Frontal area is considered to include the engine and nacelle.

The following specific assumptions are necessary to the analysis:

Ducted-fan engines. -

I - Primary cycle

(1) Diffuser pressure coefficient C_q, 0.9 (All symbols are defined in appendix A)

(2) Compressor adiabatic efficiency η_c, 0.85

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(3) Burner efficiency η_{pb}, 0.95; lower heating value of fuel, 18,550 Btu per pound (same fuel used in auxiliary burners); burner total-pressure loss due to friction and momentum, 5 percent, or $\frac{P_3}{P_2} = 0.95$

(4) Turbine-inlet temperature T_3, 2000° R; turbine adiabatic efficiency η_t, 0.9

(5) Tail-pipe-burner efficiency η_{tb}, 0.9; tail-pipe temperature T_5 limited to maximum of 3000° R; friction loss in the tail pipe burner equivalent to total-pressure loss of 7 percent, or $\frac{P_5}{P_4} = 0.93$; momentum pressure loss due to burning in tail pipe neglected

(6) Jet-nozzle adiabatic efficiency η_j, 0.94; convergent nozzles used

(7) Mass of gas through turbine equal to air mass through compressor; cooling-air loss assumed equal to mass of fuel added

(8) Turbine output equal to compressor work plus fan work

II - Secondary cycle

(1) Diffuser pressure coefficient C_q, 0.9

(2) Fan adiabatic efficiency η_f, 0.85

(3) Friction loss in secondary duct caused by burner equivalent to total-pressure loss of 7 percent, or without auxiliary burning $\frac{P_8}{P_7} = 0.93$; limiting burner temperature, 3000° R; momentum total-pressure loss due to burning, 5 percent; total-pressure loss with burning, 12 percent, or $\frac{P_8}{P_7} = 0.88$

(4) Jet-nozzle adiabatic efficiency η_j, 0.94; convergent nozzles used

<u>Turbojet engines.</u> - The assumptions applying to the turbojet engines are the same as those assumed for the primary cycle of the

ducted-fan engine except that the turbine output is equal to the compressor work.

Turbine-propeller engine. - The turbine-propeller information taken from reference 5 is based on component and combustion efficiencies that are the same as those assumed for the ducted-fan engine. The fan, however, is replaced by a propeller the propulsive efficiency of which is assumed to be 0.85 through a Mach number of 0.6 and 0.82 at a Mach number of 0.7. There are, of course, no secondary duct considerations and the auxiliary burner in the tail pipe is omitted. The turbine output is equal to the compressor work plus the propeller work. 1019

Aircraft Performance

The range study for aircraft using the various engines requires the selection of a finite engine size. A typical turbojet engine, which has a frontal area A of 4.2 square feet including the nacelle, was selected as a basis for this analysis. It is assumed that the primary unit of a ducted-fan engine can be scaled down without difficulty to maintain equal frontal areas for all engines.

The air-handling capacity of all engines is 13 pounds per second per square foot frontal area at sea level and zero flight speed. The corrected air flow is assumed to be constant at all flight conditions.

The methods of reference 5 were used to estimate the engine weights. The estimated engine weights W_e are based on a standard turbojet engine that weighs 1120 pounds and has a compressor pressure ratio of 4.12. For other compressor pressure ratios, 50 percent of the basic engine weight of 1120 pounds is considered to be fixed, 30 percent varies as the logarithm of the compressor pressure ratio, and 20 percent varies as the logarithm of the turbine pressure ratio. The fan constitutes an additional weight that is assumed equal to 30 percent of the basic engine weight for a pressure ratio of 4.12 and varies as the logarithm of the fan pressure ratio. The tail-pipe burner is assumed to weight 250 pounds and the secondary burner, 350 pounds. The size of the primary and secondary units is considered to vary in direct proportion to the respective air flows. The engine nacelle is assumed to weigh 224 pounds.

The aircraft gross weight consists of engine weight, fuel weight, fuel-tank weight, which is estimated at 10 percent of the fuel weight, pay load, and structural weight, which is considered to be 40 percent of the gross weight. It is assumed that all pay load will be obtained at the expense of displaced fuel. Pay-load-to-gross-weight ratio values of 0, 0.1, 0.2, 0.3, and 0.4 are used. The lift-drag ratio L/D (neglecting nacelle drag) and the drag coefficient C_D vary with flight Mach number M_0 in the following manner:

M_0	L/D	C_D
0.3	18.00	0.0556
.5	18.00	.0560
.6	17.21	.0580
.7	15.11	.0655
.9	10.67	.0870

The decrease in L/D with increasing flight Mach number permits a constant wing loading of 80 pounds per square foot.

With the use of these assumptions to determine the engine size and the corresponding aircraft, the range is calculated in a manner similar to that of reference 5.

The mathematical expressions required for the analysis are given in appendix B.

RESULTS AND DISCUSSION

Maximum-Thrust Engines

The effect of the ratio of the power to the fan to the available fan power ϕ and the ratio of secondary air flow to primary air flow W_r on net thrust per pound of air handled by ducted-fan engines with auxiliary burning at a Mach number of 0.3 is illustrated in figure 2. The corresponding change in net-thrust specific fuel consumption is also shown. The curve indicates that the maximum net thrust per pound of air handled is obtained by reducing ϕ and W_r to zero. The ducted-fan engine with auxiliary burning therefore evolves into a turbojet engine with tail-pipe burning. A calculation of maximum net thrust per pound of air handled at a flight Mach number of 0.9 gave similar results. It can also be seen (fig. 2) that ducted-fan engines with auxiliary burning not only develop a lower net thrust per pound of air handled but show an increase in net-thrust specific fuel consumption as compared to a turbojet engine with tail-pipe burning. The optimum compressor pressure ratio used for determining the maximum thrust of the ducted-fan engine with auxiliary burning is the same as that of the turbojet engine with tail-pipe burning.

Ducted-fan engines can produce an equal or higher thrust per unit frontal area only if compared with turbojet engines having a lower air-handling capacity per unit frontal area (fig. 2).

The maximum obtainable net thrust per pound of air handled and the corresponding net-thrust specific fuel consumption at various flight Mach numbers for turbojet engines with tail-pipe burning are shown in figure 3. At these conditions turbojet engines with tail-pipe burning represent the optimum configurations of maximum-thrust ducted-fan engines with auxiliary burning. The approximate compressor pressure ratio P_2/P_1 for obtaining maximum net thrust per pound of air handled is also plotted in figure 3, against Mach number for turbojet engines with tail-pipe burning. The decrease of compressor pressure ratio with flight speed is such that the product of compressor pressure ratio and ram pressure ratio is approximately constant over the speed range. This constancy is coincidental inasmuch as the compressor pressure ratio decreases with Mach number for the condition of maximum thrust as a result of the decreasing ratio of turbine-inlet to engine-inlet temperatures. The compressor pressure ratios shown in figure 3 tend to produce the maximum propulsive jet velocity.

Maximum-Economy Engines

The variation of minimum obtainable net-thrust specific fuel consumption and corresponding net thrust per pound of air handled with flight Mach number is shown in figure 4 for ducted-fan and turbojet engines. Values of net-thrust specific fuel consumption are also shown for the turbine-propeller engine but are not necessarily minimums because the engine is of constant pressure ratio. These values do, however, demonstrate the capacity of the turbine-propeller engine to operate at substantially lower values of net-thrust specific fuel consumption below a flight Mach number of approximately 0.85 than ducted-fan and turbojet engines. The turbine-propeller data are taken from reference 5.

At a Mach number of 0.3, the net-thrust specific fuel consumption of a ducted-fan engine is 27 percent lower than that of a turbojet engine. This difference diminishes to approximately 4 percent at a Mach number of 0.9. The low net-thrust specific fuel consumption is accompanied, however, by low values of net thrust per pound of air. These values are only 27 to 64 percent (depending on the flight Mach number) of the net thrust per pound of air produced by turbojet engines. A plot of the net thrust per pound of air handled by the turbine-propeller engine is omitted because of lack of a comparable basis of presentation.

The values of fan pressure ratio P_7/P_1, ϕ, and W_r required to obtain minimum net-thrust specific fuel consumption over the range of Mach numbers considered are presented in figure 5. The fan pressure ratio increases with increasing Mach number whereas both the power input to the fan and the secondary air flow decrease with increasing Mach number. The increasing fan pressure ratio is the result of the secondary air flow decreasing at a greater rate than the fan power input. The approximate compressor pressure ratios necessary to provide minimum obtainable net-thrust specific fuel consumption are also shown in figure 5 for ducted-fan and turbojet engines for the range of flight Mach numbers considered.

The convergence of the curves of figures 4 and 5 indicate the conversion of the ducted-fan engine into a turbojet engine at a flight Mach number greater than 0.9. A separate calculation locates the end point of this trend at a flight Mach number of approximately 1.2.

Maximum-Range Engines

In order to determine the maximum flight range of various airplane-engine configurations, it is necessary to calculate the values of three important engine parameters: specific fuel consumption sfc, net thrust F_n, and engine weight W_e. The interrelation of these parameters is complex to the extent that it is impossible to obtain maximum flight range by powering an airplane with either a maximum-economy or a maximum-thrust type of turbojet engine.

A maximum-economy type of turbojet engine requires a high compressor pressure ratio, or greater engine weight, and produces a low thrust per pound of air, which results in an extremely high specific engine weight W_e/F_n.

A maximum-thrust type of turbojet engine, although possessing a low specific engine weight, is unable to operate at a sufficiently low value of specific fuel consumption. A compromise is therefore necessary. The discussion that follows indicates what this compromise should be.

A plot of maximum obtainable range against flight Mach number is presented in figure 6 for ducted-fan and turbojet engines at several ratios of pay load to gross weight. Ducted-fan engines show a substantially greater range at flight Mach numbers below 0.6 and pay-load-to-gross-weight ratios below 0.3 than turbojet engines. This difference is negligible at either higher flight Mach numbers or greater pay-load-to-gross-weight ratios. The greater range for the ducted-fan engine over the turbojet engine at flight Mach numbers below 0.6 is of little consequence, however, inasmuch as the maximum flight range for both engines occurs at a flight Mach number of approximately 0.6. At this speed, and at zero pay load the ducted-fan shows a range increase of only 5 percent over the turbojet engine.

The variation in range with flight Mach number at various pay-load-to-gross-weight ratios for the turbine-propeller engine described in reference 5 is also shown in figure 6. Although the range performance is not necessarily a maximum because of constant pressure ratio, a marked range advantage is indicated for the turbine-propeller engine as compared with the turbojet-type engines below a flight Mach number of 0.6.

The approximate values of fan pressure ratio, ϕ, W_r, and compressor pressure ratios necessary to obtain maximum range at various flight Mach numbers with ducted-fan engines are presented in figure 7. Corresponding pressure ratios are also shown for turbojet engines. The trend of these curves is similar to the trends indicated in figure 5. In figure 7, the ducted-fan engine reverts to a turbojet engine at a flight Mach number of 0.8.

It can be seen in figure 7 that ϕ and W_r are unaffected by the pay-load-to-gross-weight ratio; however, the fan pressure ratio increases and the compressor pressure ratio decreases with an increasing pay-load-to-gross-weight ratio. The decreased compressor pressure ratio has a greater effect on range than the increased fan pressure ratio in that the total engine weight and the net-specific engine weight are reduced, as shown in figure 8. A factor contributing to the improved specific engine weight is an increase in net thrust per pound of air with increased pay-load-to-gross-weight ratio, which is shown in figure 9.

Although ducted-fan maximum-range engines are lighter than turbojet maximum-range engines, apparently because of the higher compressor pressure ratios of the turbojet engines, the specific weights of the turbojet engines are lower (fig. 8). The favorable specific weights of these engines permit their maximum range to equal or exceed that of the ducted-fan engines at flight Mach numbers above 0.65 or pay-load-to-gross-weight ratios of 0.3 and above.

One of the anticipated advantages of a ducted-fan engine is a low specific weight relative to turbojet engines. If ducted-fan engines are compared with turbojet engines of equal air-handling capacity per unit frontal area, however, a lower specific weight is not indicated (fig. 8).

In addition to the values of net thrust per pound of air shown in figure 9, the corresponding net-thrust specific fuel consumption is presented for maximum-range ducted-fan and turbojet engines operating at various flight Mach numbers and several pay-load-to-gross-weight ratios. Although specific fuel consumption is a commonly accepted index of jet-engine performance, a comparison of figure 9 with figure 4 (minimum net-thrust specific fuel consumption) shows that a low specific fuel consumption is not necessarily a criterion of the best-range type of turbojet engine.

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If flight speeds do not exceed a flight Mach number of approximately 0.6, the turbine-propeller engine should offer the most favorable performance of any of the engines considered. If, however, higher flight Mach numbers are desired, the turbojet engine with tail-pipe burner (operating for maximum thrust and nonoperative for achieving greater range) should provide the greatest flexibility of all the engines considered.

SUMMARY OF RESULTS

According to performance evaluation of ducted-fan engines relative to turbojet and turbine-propeller engines, based on equal air flow per unit frontal area, the following results were obtained:

1. The turbojet engine with tail-pipe burning produced greater thrust per pound of air handled than any configuration of ducted-fan engine.

2. At flight Mach numbers up to 0.85, the turbine-propeller engine provided the lowest specific fuel consumption of any of the engines investigated. Ducted-fan engines designed for minimum net-thrust specific fuel consumption operated at 27 and 4 percent lower values, at flight Mach numbers of 0.3 and 0.9, respectively, than those obtainable from turbojet engines designed to obtain minimum specific fuel consumption.

3. Below a flight Mach number of 0.6 and for pay-load-to-gross-weight ratios of 0.3 or less, the turbine-propeller engine realized the greatest range of any of the engines considered. Maximum range for both ducted-fan and turbojet engines occurred at a flight Mach number of approximately 0.6. At this speed and for zero pay load, the ducted-fan engine showed a 5-percent increase in range over the turbojet engine. At higher flight Mach numbers or at a pay-load-to-gross-weight ratio of 0.3 or greater, the increase in range was negligible.

CONCLUSIONS

From the preceding results, the following conclusions are drawn:

1. Ducted-fan engines show a higher thrust per unit frontal area only if compared with turbojet engines of lower air-handling capacity per unit frontal area.

2. If ducted-fan engines are compared with turbojet engines of equal air-handling capacity per unit frontal area, no improvement in specific weight is indicated.

3. If flight speeds do not exceed a flight Mach number of approximately 0.6, the turbine-propeller engine should offer the most favorable performance of any of the engines considered. If, however, higher flight Mach numbers are desired, the turbojet engine with tail-pipe burner (operating for maximum thrust and nonoperative for achieving greater range) should provide the greatest flexibility of all the engines considered.

Lewis Flight Propulsion Laboratory,
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APPENDIX A

SYMBOLS

The following symbols are used in the analysis:

A	frontal area, sq ft
C_D	nacelle drag coefficient
C_q	diffuser pressure coefficient, $\dfrac{P_1 - p_0}{P_0 - p_0}$
c_p	specific heat at constant pressure, Btu/(lb)($^\circ$F)
D_n	nacelle drag, lb
F_n	net thrust, lb
f	fuel-air ratio
g	acceleration due to gravity, 32.18, ft/sec^2
Δh	change in enthalpy, Btu/lb
J	mechanical equivalent of heat, 778, ft-lb/Btu
L/D	lift-drag ratio of aircraft without nacelles
M_0	flight Mach number
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
q	dynamic pressure, lb/sq ft
R	gas constant, 53.3, ft-lb/(lb)($^\circ$F)
sfc	specific fuel consumption, lb/hr/(lb thrust)
T	total temperature, $^\circ$R
t	static temperature, $^\circ$R
V	velocity, ft/sec

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W_a air flow, lb/sec

W_e engine weight, lb

W_r $\frac{\text{secondary air flow}}{\text{primary air flow}}$

γ ratio of specific heats

η adiabatic efficiency

ϕ $\frac{\text{power to fan}}{\text{available fan power}} = \frac{\text{power to fan}}{\text{maximum available turbine power} - \text{compressor work}}$

Subscripts:

0 ambient atmosphere

1 compressor and fan inlet

2 compressor outlet

3 turbine inlet

4 turbine outlet

5 tail-pipe and auxiliary-burner inlet

6 jet-nozzle throat

7 fan outlet

8 auxiliary-burner inlet (secondary burner)

9 jet-nozzle throat (secondary jet)

avail available turbine work

c compressor

f fan

j jet

pb primary burner

pj	primary jet
sb	secondary burner
sj	secondary jet
t	turbine
tb	tail-pipe burner

APPENDIX B

METHOD OF ANALYSIS

Engine Performance

The analysis of the ducted-fan engines follows the assumptions listed in the section BASIS OF ANALYSIS. The net thrust per pound of air flow and the specific fuel consumption are derived from the enthalpy changes across the engine components. The turbine is considered capable of converting all the maximum available energy for driving the compressor and the fan. Maximum available energy is herein defined as the energy obtainable as the result of the expansion of the gases in the turbine from the turbine-inlet pressure to atmospheric back pressure, or

$$\Delta h_{avail} = c_{p,t} T_3 \eta_t \left[1 - \left(\frac{p_0}{P_3} \right)^{\frac{\gamma_t - 1}{\gamma_t}} \right] \tag{1}$$

The compressor work is

$$\Delta h_c = c_{p,c} \frac{T_1}{\eta_c} \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma_c - 1}{\gamma_c}} - 1 \right] \tag{2}$$

The fan work is assumed to be a function of the available turbine energy after deducting compressor work

$$W_r \Delta h_f = W_r c_{p,f} \ (T_7 - T_1) = W_r c_{p,f} \frac{T_1}{\eta_f} \left[\left(\frac{P_7}{P_1} \right)^{\frac{\gamma_f - 1}{\gamma_f}} - 1 \right] = \phi \ (\Delta h_{avail} - \Delta h_c) \tag{3}$$

The work required of the turbine can now be found from

$$\Delta h_t = c_{p,t} \ (T_3 - T_4) = c_{p,t} T_3 \eta_t \left[1 - \left(\frac{P_4}{P_3} \right)^{\frac{\gamma_t - 1}{\gamma_t}} \right] = \Delta h_c + W_r \Delta h_f \tag{4}$$

The net thrust per pound of air flow is computed from the following relation:

$$\frac{F_n}{W_a} = \frac{1}{W_r+1}\left[\frac{V_6}{g} + \frac{A_6}{W_a}\left(p_6 - p_0\right)\right] + \frac{W_r}{W_r+1}\left[\frac{V_9}{g} + \frac{A_9}{W_a}\left(p_9 - p_0\right)\right] - \frac{V_0}{g} \qquad (5)$$

where V_6, p_6, and $\frac{A_6}{W_a}$ and V_9, p_9, and $\frac{A_9}{W_a}$ are found from the following equations:

$$\left.\begin{aligned} V_6^{\,2} &= 2gJc_{p,pj}T_5\eta_j\left[1 - \left(\frac{p_6}{P_6}\right)^{\frac{\gamma_{pj}-1}{\gamma_{pj}}}\right] \\ p_6 &= P_6\left(\frac{2}{\gamma_{pj}+1}\right)^{\frac{\gamma_{pj}}{\gamma_{pj}-1}} \text{ or } p_0, \text{ whichever is greater} \\ \frac{A_6}{W_a} &= \frac{Rt_6}{p_6V_6} \end{aligned}\right\} \qquad (6)$$

$$\left.\begin{aligned} V_9^2 &= 2gJc_{p,sj}T_8\eta_j\left[1-\left(\frac{p_9}{P_9}\right)^{\frac{\gamma_{sj}-1}{\gamma_{sj}}}\right] \\ p_9 &= P_9\left(\frac{2}{\gamma_{sj}+1}\right)^{\frac{\gamma_{sj}}{\gamma_{sj}-1}} \text{ or } p_0, \text{ whichever is greater} \\ \frac{A_9}{W_a} &= \frac{Rt_9}{p_9V_9} \end{aligned}\right\} \tag{7}$$

The fuel-air ratio for the complete engine cycle is then found from the following equation:

$$f = \frac{\frac{c_{p,pb}}{\eta_{pb}}(T_3 - T_2) + \frac{c_{p,tb}}{\eta_{tb}}(T_5 - T_4) + W_r\frac{c_{p,sb}}{\eta_{sb}}(T_8 - T_7)}{18,550\ (W_r + 1)} \tag{8}$$

and from equations (5) and (8), the specific fuel consumption is calculated

$$\text{sfc} = \frac{3600\ f}{F_n/W_a} \tag{9}$$

The values used for c_p and γ are functions of the corresponding temperatures. Optimum values for the compressor pressure ratio P_2/P_1, the ratio of the power to the fan to the available fan power ϕ, and the ratio of secondary air flow to primary air flow W_r for each flight Mach number M_0 are determined by graphical solution.

The analysis of the turbojet engine is the same as the ducted-fan-engine analysis when W_r and ϕ are equal to zero.

Aircraft Performance

With the assumptions listed in the section BASIS OF ANALYSIS, the weight of each ducted-fan engine is computed as

$$W_e = \frac{560 + 542 \log\left(\frac{P_2}{P_1}\right) + 470 \log\left(\frac{P_3}{P_4}\right) + 542\, W_r \log\left(\frac{P_7}{P_1}\right)}{W_r + 1} + \frac{250 + 350\, W_r}{W_r + 1} + 224 \qquad (10)$$

in which the second term consists of the tail-pipe burner and the secondary-burner weights. This expression is adaptable to the turbojet engine when W_r is equal to zero.

The range of the aircraft is then computed using the method of reference 5 from which the following expression is derived:

$$\text{Range} = \frac{\left(\frac{3600}{5280}\right) V_0 \frac{L}{D}\left(1 - \frac{D_n}{F_n}\right)}{\text{sfc}} \left\{ - \log_e \left[1 - \frac{1}{1.1}\left(0.6 - \frac{\text{pay load}}{\text{gross weight}} - \frac{\frac{W_e}{F_n}}{\frac{L}{D}\left(1 - \frac{D_n}{F_n}\right)} \right) \right] \right\} \qquad (11)$$

where

$$D_n = C_D q A \qquad (12)$$

The values of 1.1 and 0.6 appearing in equation (11) represent fuel plus fuel-tank weight and gross airplane weight less structural weight, respectively.

Equation (11) assumes that the ratios L/D and V_0/sfc remain constant during a flight.

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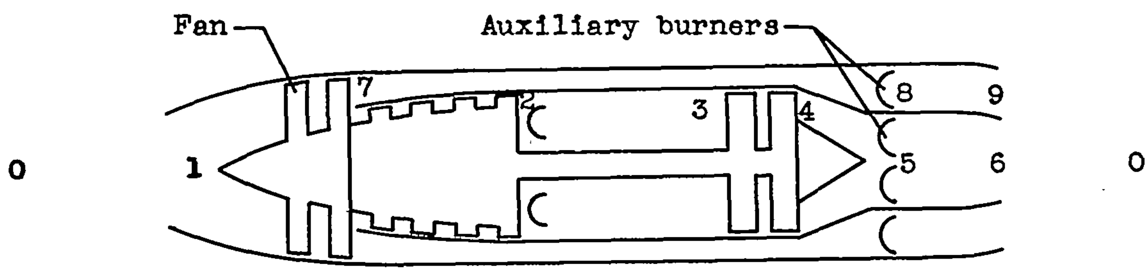
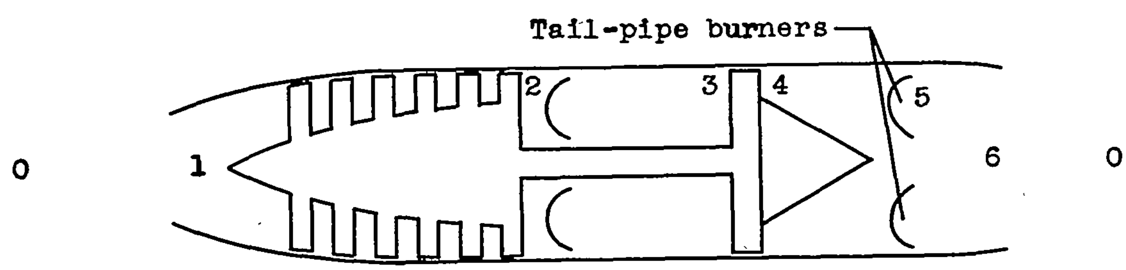
Station

0 Ambient atmosphere
1 Compressor and fan inlet
2 Compressor outlet
3 Turbine inlet
4 Turbine outlet
5 Tail-pipe- and auxiliary-burner inlet
6 Jet nozzle throat
7 Fan outlet
8 Auxiliary-burner inlet (secondary burner)
9 Jet-nozzle throat (secondary jet)



(a) Ducted-fan engine.



(b) Turbojet engine.

Figure 1. - Schematic diagrams of ducted-fan engine and turbojet engine, including auxiliary burners.

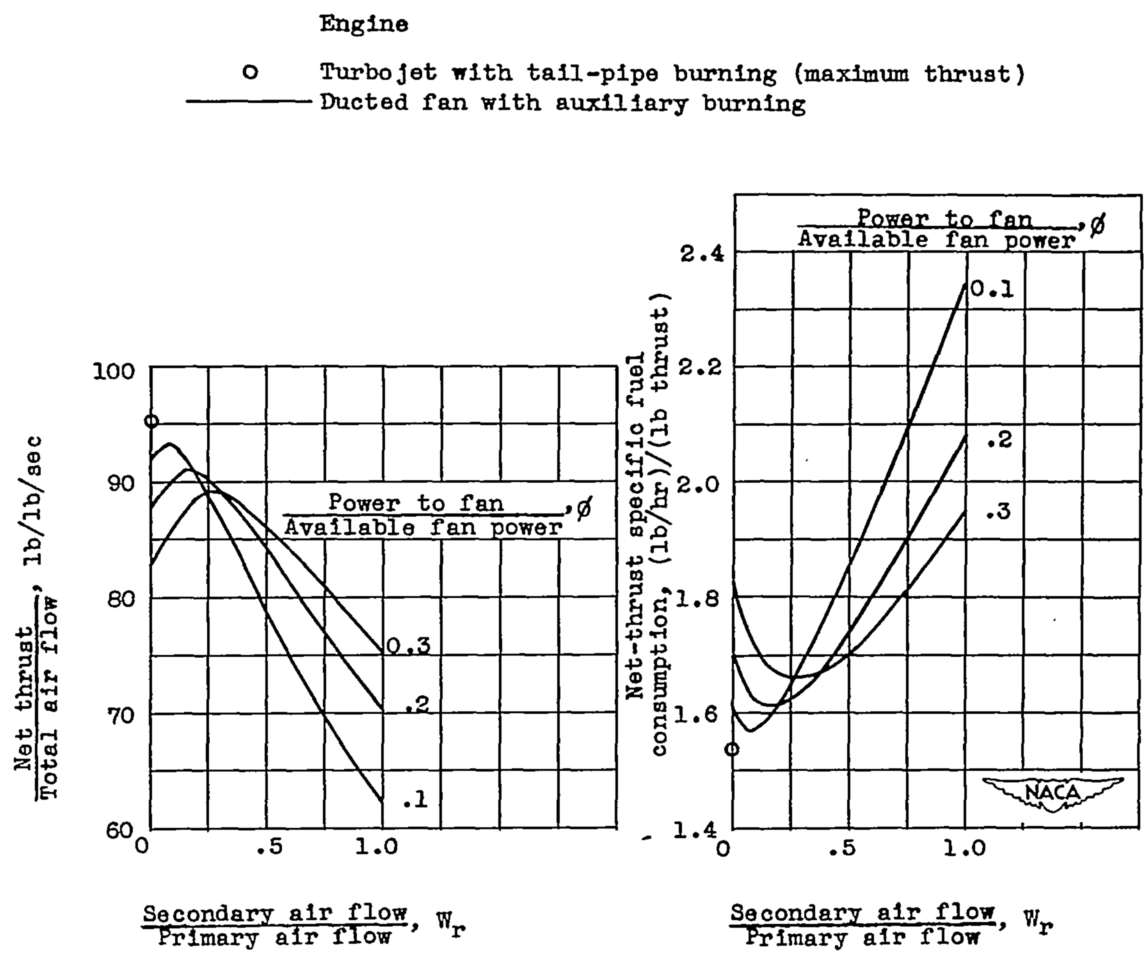


Figure 2. - Effect of varying ratio of secondary air flow to primary air flow and ratio of power to fan to available fan power with net thrust per pound of air and net-thrust specific fuel consumption for ducted-fan engines with auxiliary burning. Mach number, 0.3; altitude, 30,000 feet.

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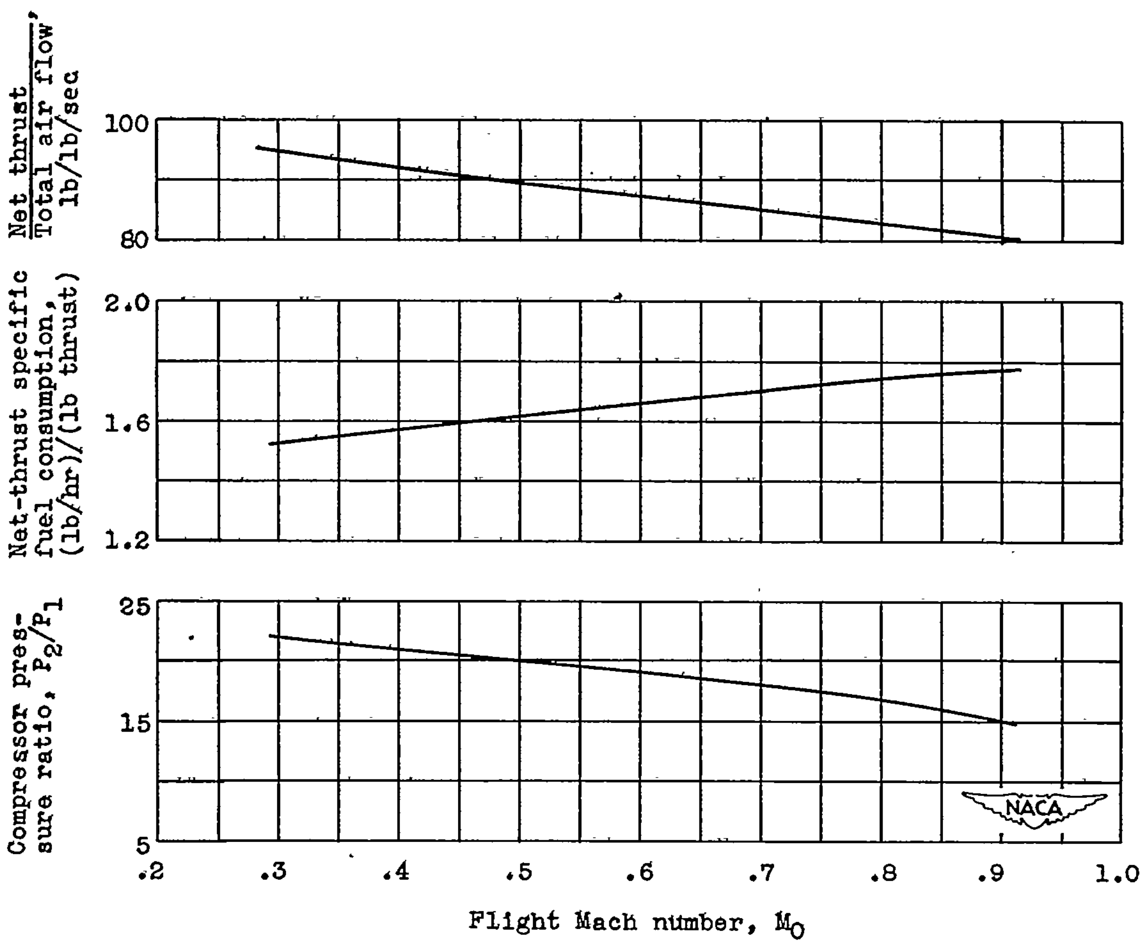

Figure 3. - Net thrust per pound of air, net-thrust specific fuel consumption, and compressor pressure ratio for maximum-thrust turbojet engines with tail-pipe burning (optimum configuration of ducted-fan engine with auxiliary burning) at various flight Mach numbers. Altitude, 30,000 feet.

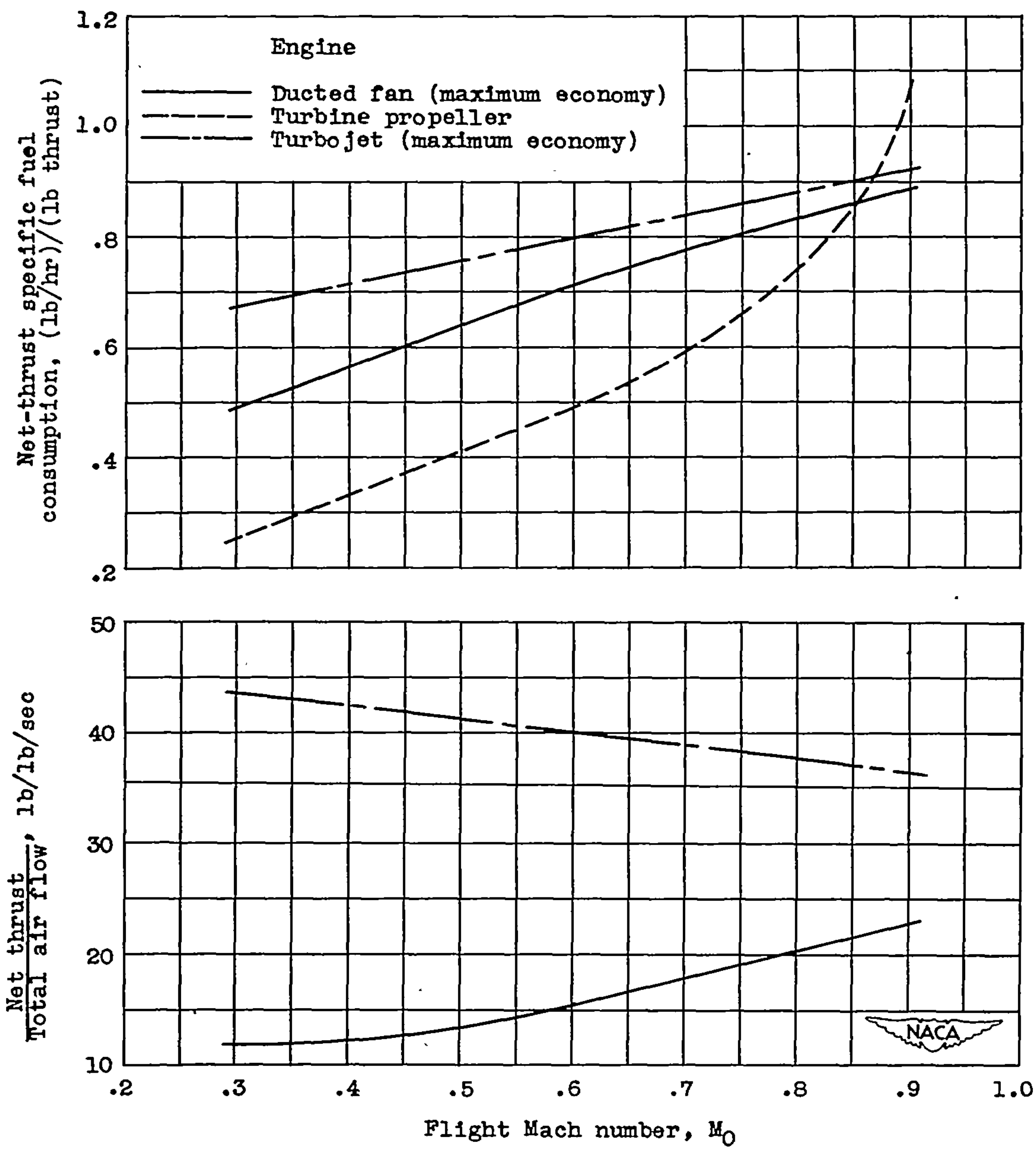

Figure 4. - Net thrust per pound of air and net-thrust specific fuel consumption for maximum-economy ducted-fan and turbojet engines at various flight Mach numbers. (Net-thrust specific fuel consumption also shown for turbine-propeller engine.) Altitude, 30,000 feet.

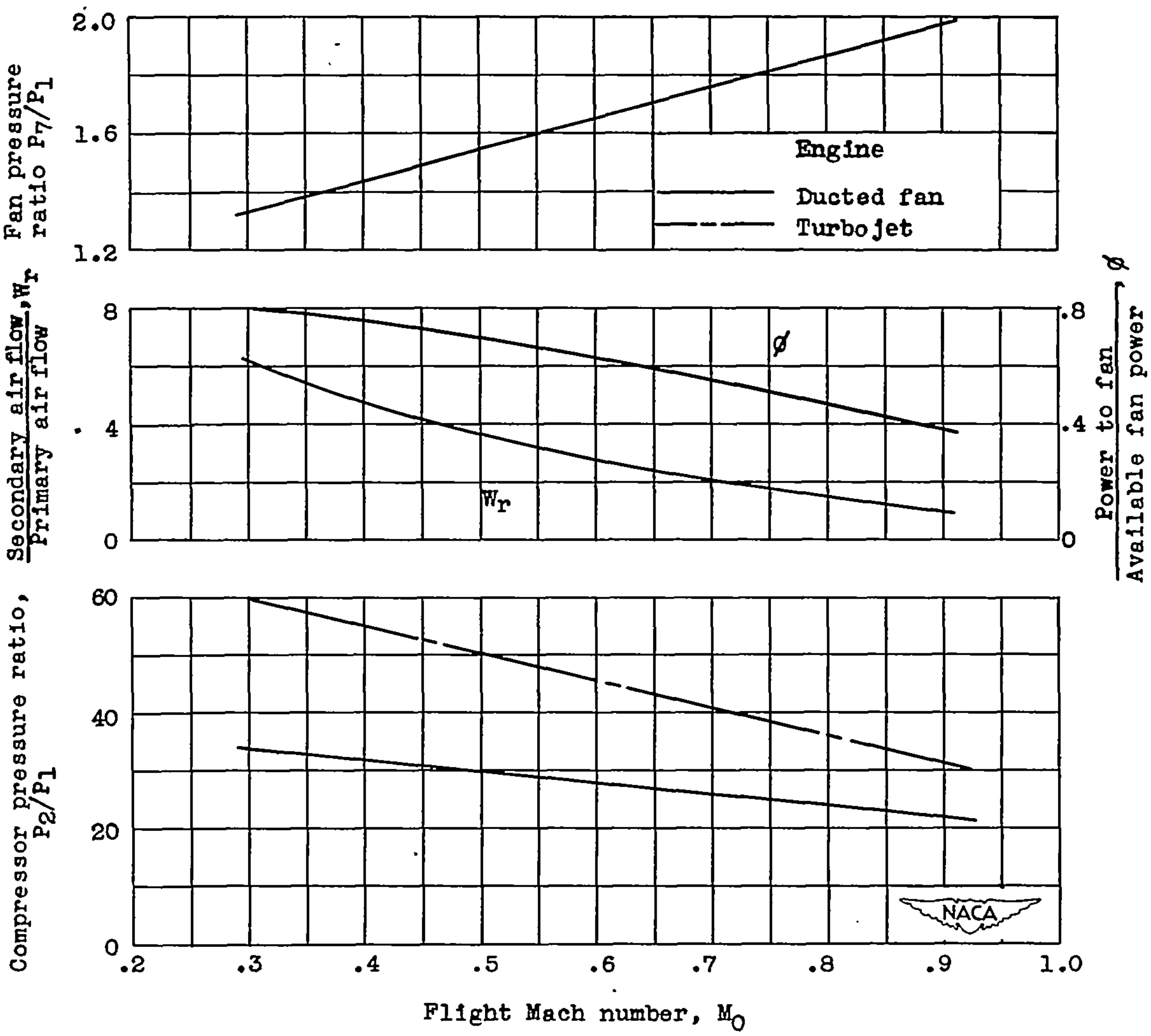

Figure 5. - Approximate variation with flight Mach number of fan pressure ratio, ratio of power to fan to available fan power, ratio of secondary air flow to primary air flow, and compressor pressure ratio necessary to permit ducted-fan engines to operate with maximum economy. (Required compressor pressure ratios also shown for turbojet engine operating at maximum economy.) Altitude, 30,000 feet.

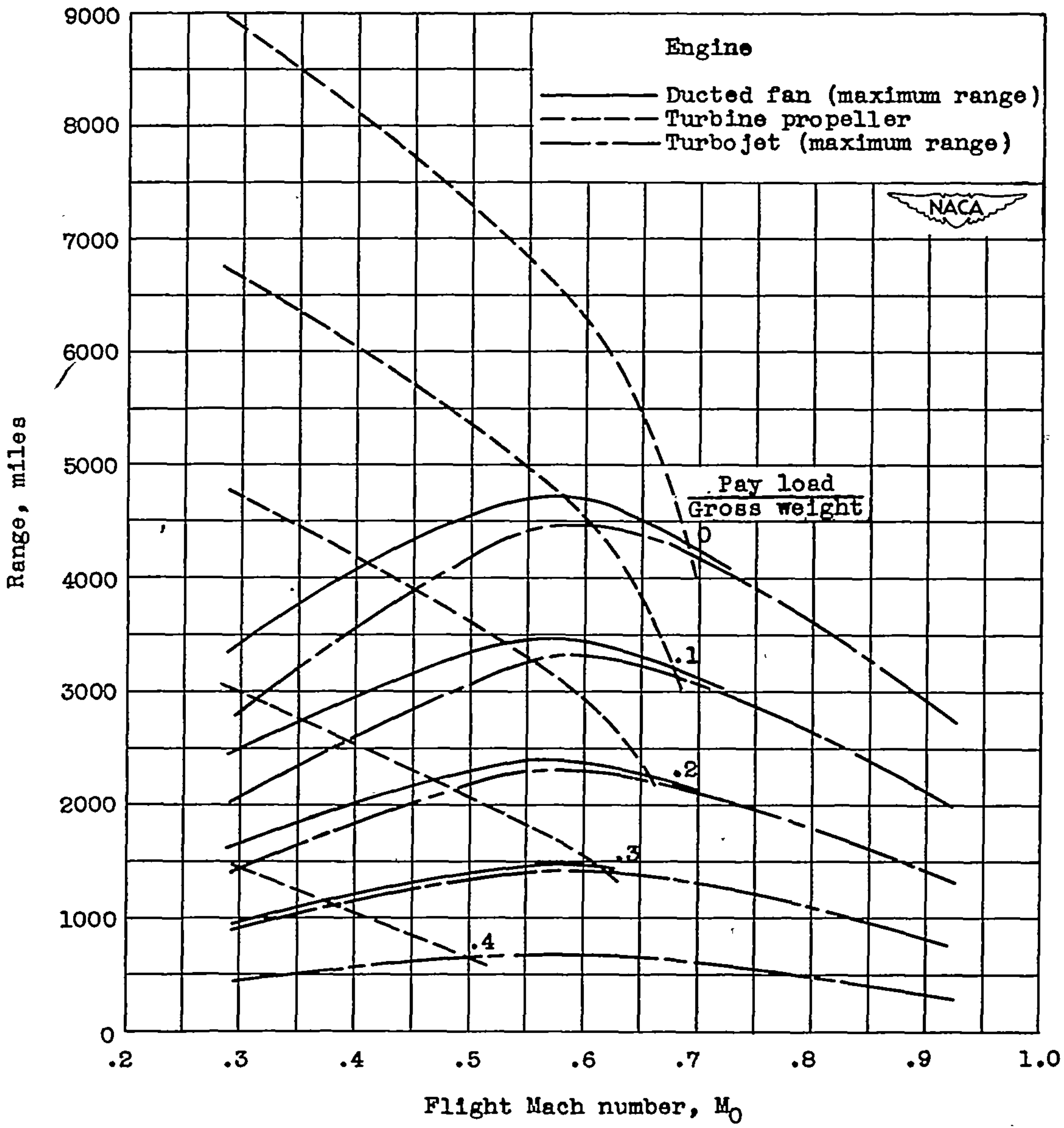

Figure 6. - Flight range of maximum-range ducted-fan and turbojet engines for several ratios of pay load to gross weight at various flight Mach numbers. (Flight range of turbine-propeller engine also shown.) Altitude, 30,000 feet.

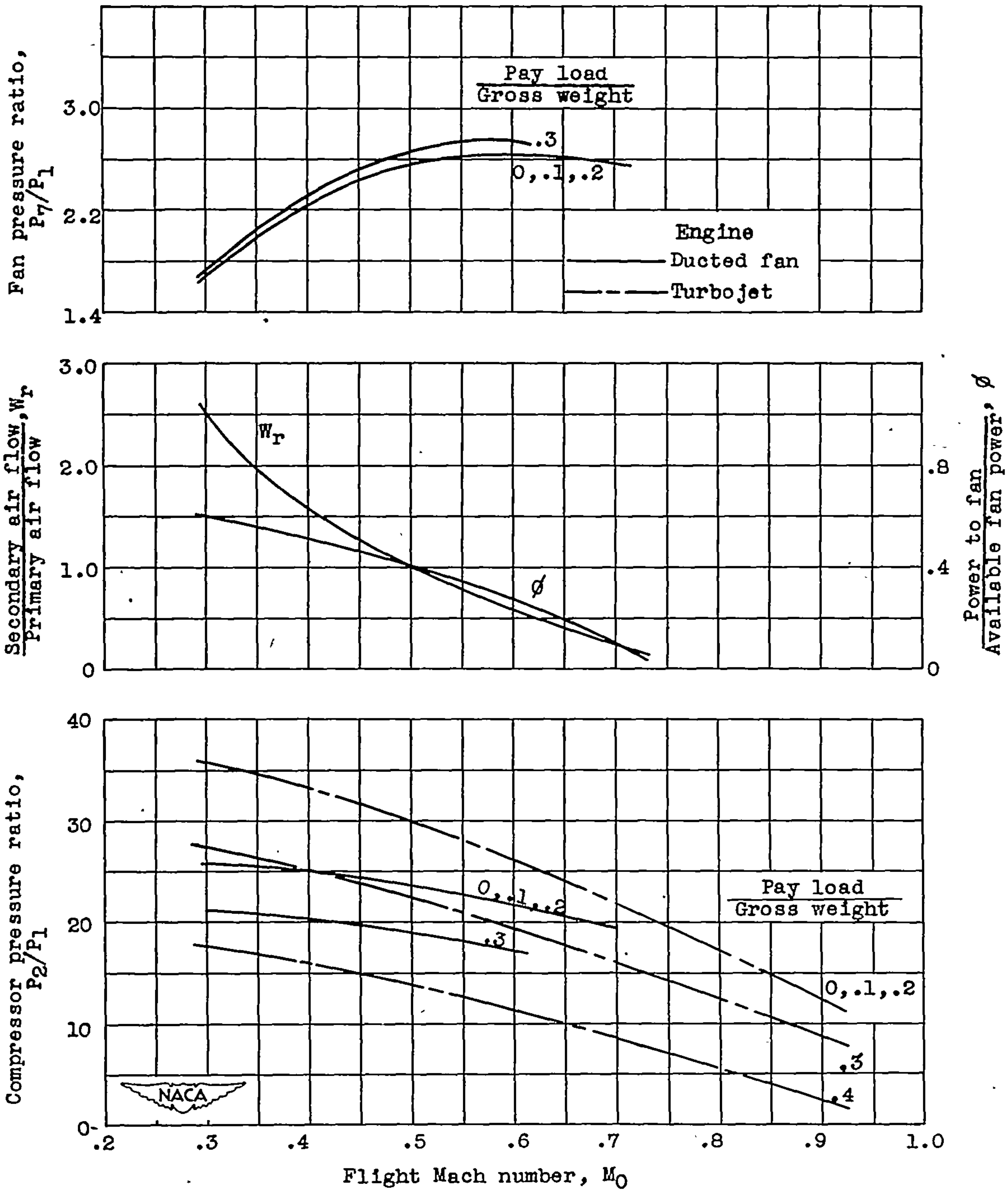

Figure 7. - Approximate variation with flight Mach number of fan pressure ratio, ratio of power to fan to available fan power, ratio of secondary air flow to primary air flow, and compressor pressure ratio (at several values of pay-load-to-gross-weight ratio) necessary to permit ducted-fan engines to attain maximum flight range. (Corresponding pressure ratios shown for turbojet engine.) Altitude, 30,000 feet.

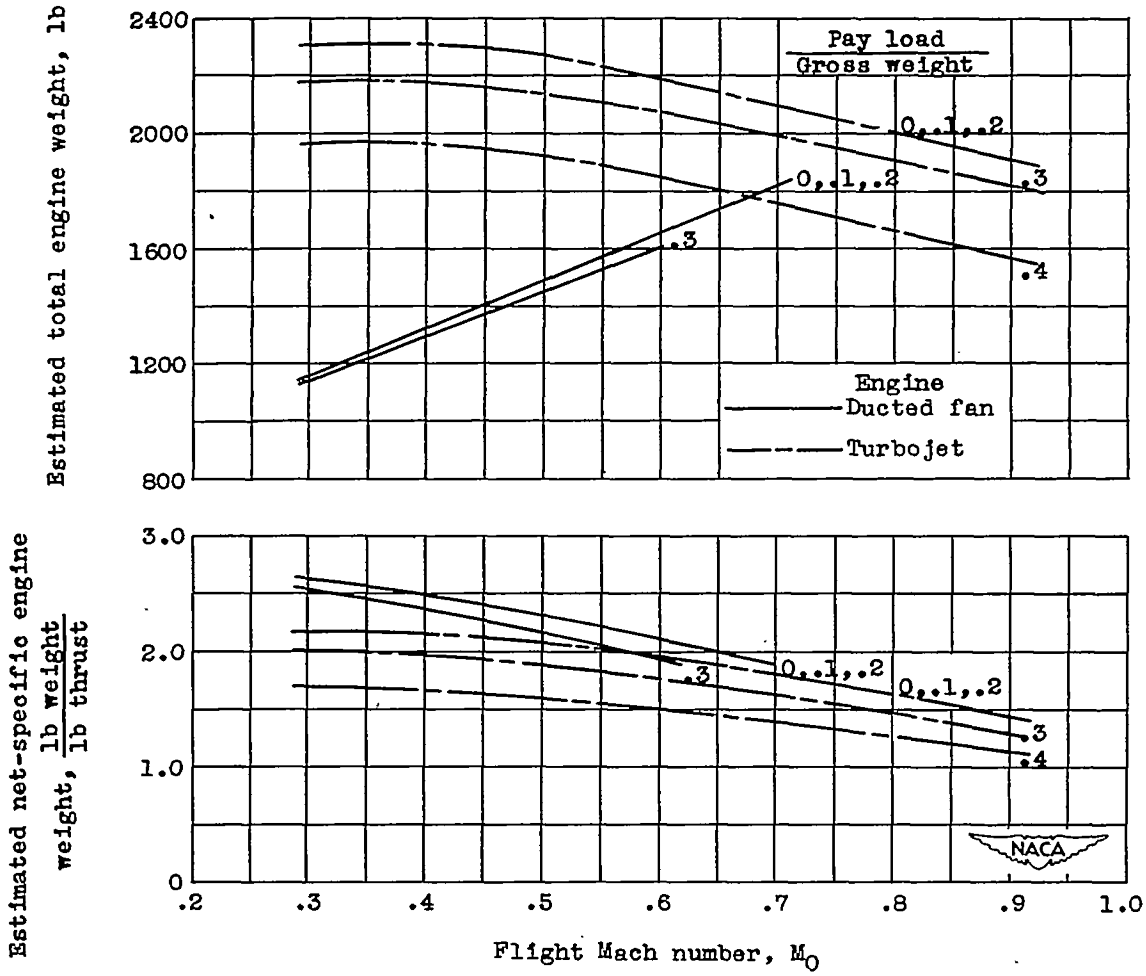

Figure 8. - Estimated engine weight and net-specific engine weight of maximum-range ducted-fan and turbojet engines at various flight Mach numbers for several values of pay-load-to-gross-weight ratio. Altitude, 30,000 feet.

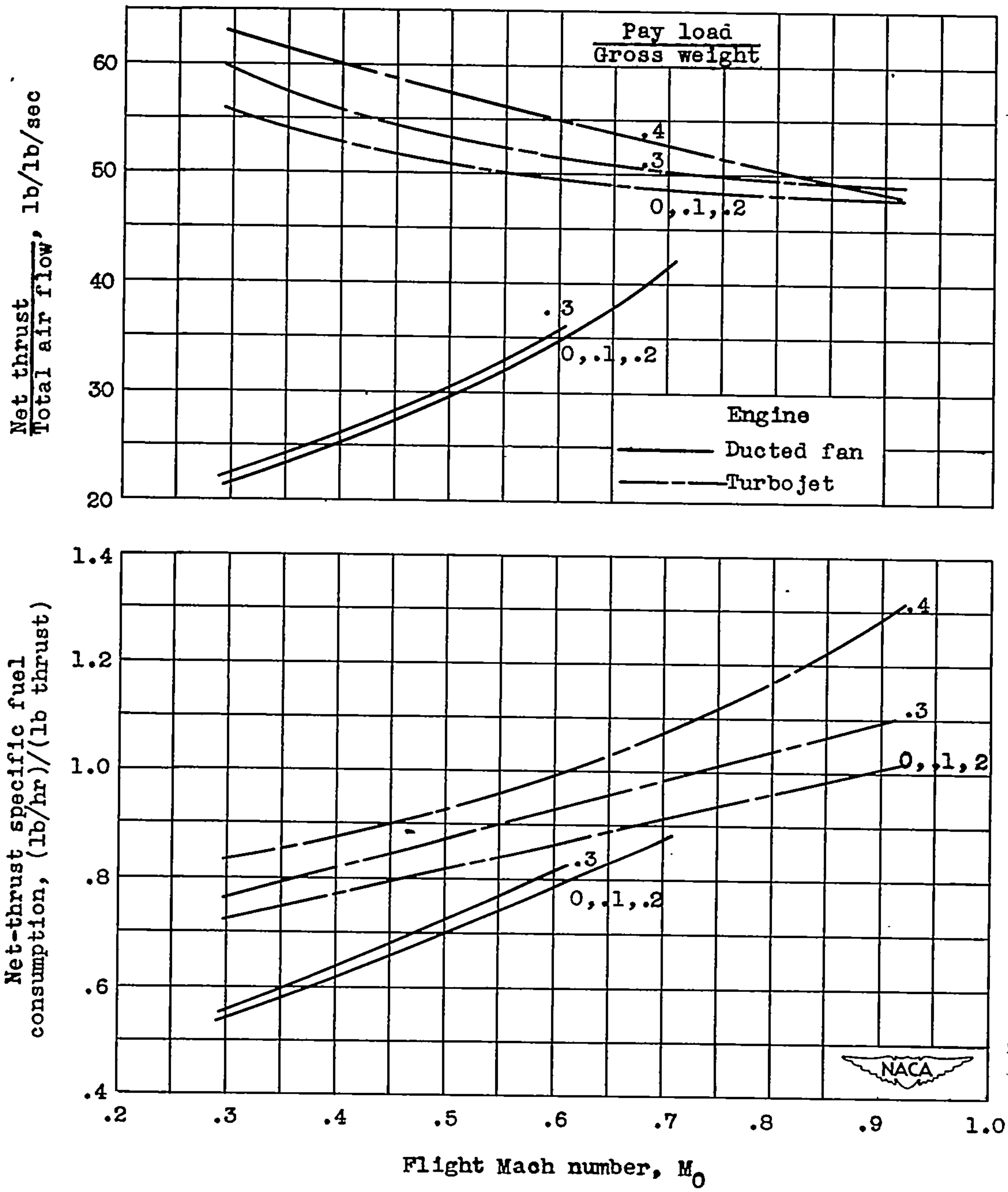

Figure 9. - Net thrust per pound of air and net-thrust specific fuel consumption of maximum-range ducted-fan and turbojet engines for several ratios of pay load to gross weight at various flight Mach numbers. Altitude, 30,000 feet.